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# TECHNICAL NOTE

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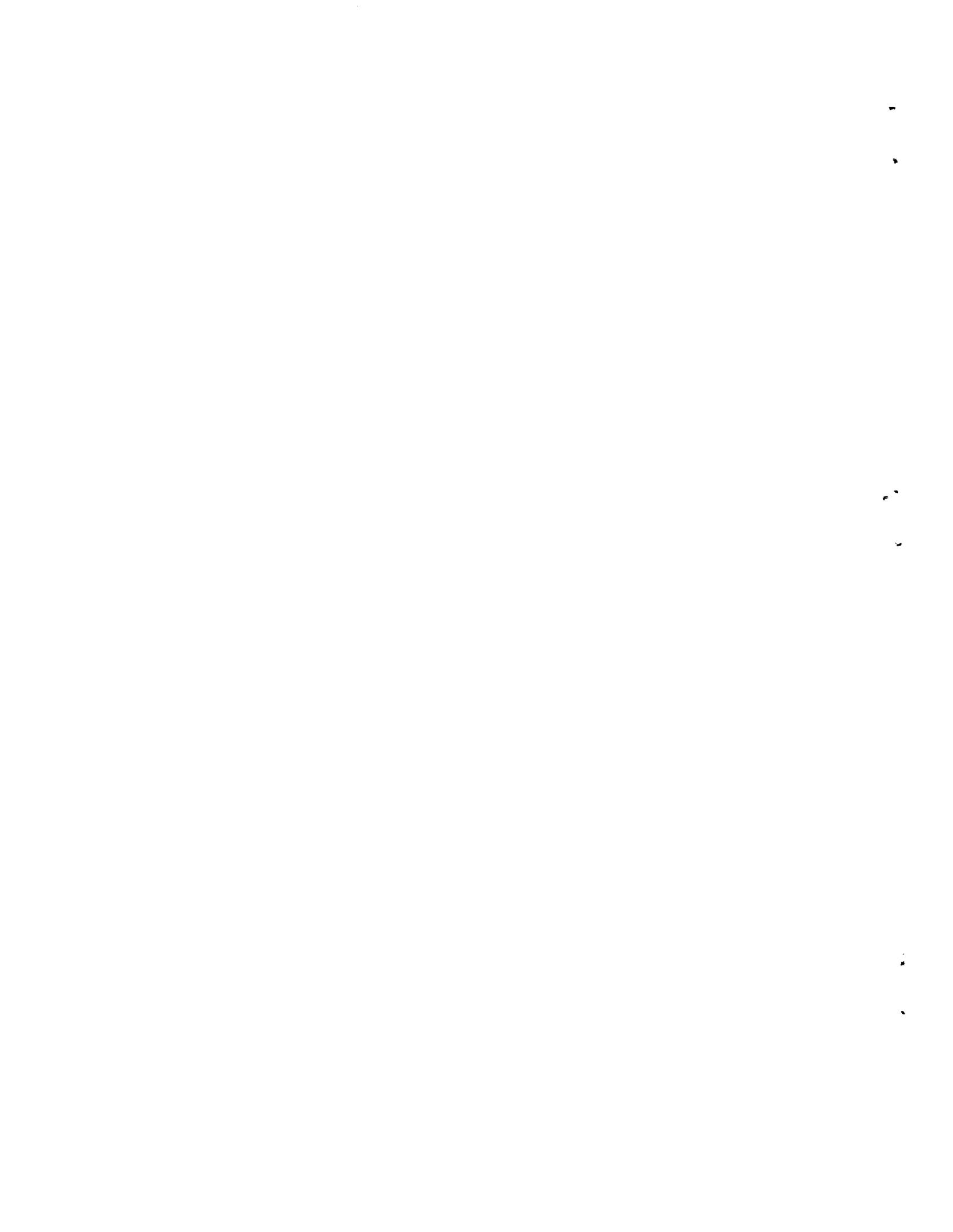
## IONOSPHERIC MEASUREMENTS USING ENVIRONMENTAL SAMPLING TECHNIQUES

R. E. Bourdeau, J. E. Jackson, J. A. Kane, and G. P. Serbu

Goddard Space Flight Center

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION  
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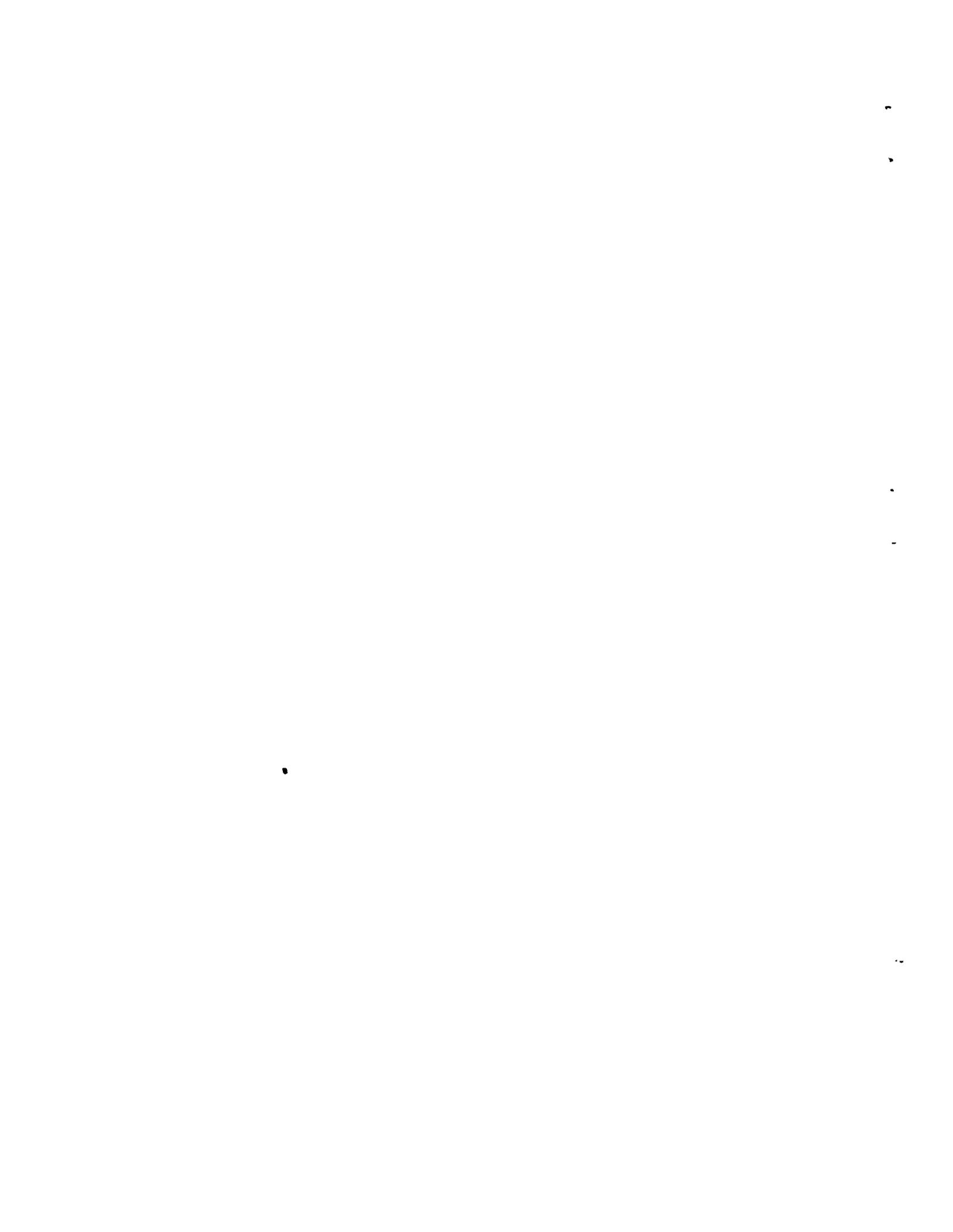
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## SUMMARY

Two rockets were flown to peak altitudes of 220 km in September 1959 to test various methods planned for future measurements of ionization parameters in the ionosphere, exosphere, and interplanetary plasma. The experiments used techniques which sample the ambient environment in the immediate vicinity of the research vehicle. Direct methods were chosen since indirect propagation techniques do not provide the temperatures of charged particles, are insensitive to ion densities, and cannot measure local electron densities under all conditions. Very encouraging results have been obtained from a preliminary analysis of data provided by one of the two flights.

A new rf probe technique was successfully used to determine the electron density profile. This was indicated by its agreement with the results of a companion cw propagation experiment, particularly when the probe data were corrected for the effects of the ion sheath which surrounds the vehicle. The characteristics of this sheath were determined directly in flight by an electric field meter which provided the sheath field, and by a Langmuir probe which measured the total potential across the sheath.

The electron temperatures deduced from the Langmuir probe data are greater than the neutral gas temperatures previously measured for the same location and season, but these measurements possibly were taken under different atmospheric conditions. Ion densities were calculated from the ion trap data for several altitudes ranging from 130 to 210 km and were found to be within 20 percent of the measured electron densities.



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# IONOSPHERIC MEASUREMENTS USING ENVIRONMENTAL SAMPLING TECHNIQUES \*

## INTRODUCTION

A comprehensive study of the nature of ionization in space requires simultaneous measurements of the following parameters: the electron and ion concentrations and thermal energies, and the ion compositions.

The vertical electron density profile of the undisturbed ionosphere is fairly well known up to the height of the maximum electron density,  $h_{\max} F_2$ , usually about 300 to 400 km above the earth's surface. Typical profiles were first established from rocket measurements employing Seddon's cw propagation experiments (Reference 1). These data resolved ambiguities present in P' - f ground observations (Reference 2) and "bottomside" profiles can now be obtained from many locations.

Relatively little is known concerning the disturbed ionosphere below  $h_{\max} F_2$ , about the topside ionosphere, the exosphere, and the interplanetary plasma. Uncertainties by a factor of 10 are common regarding ionospheric irregularities or electron densities in the upper ionosphere. Electron densities, however, are by far the best known ionospheric parameter.

Although ion composition measurements are not discussed in the present paper it can be stated that present techniques can provide ion composition for altitudes ranging from 100 to about 5000 km. New techniques are needed, however, to investigate the other ionospheric parameters mentioned earlier. Past investigations were usually limited to measurements of one or, at most, two parameters during a given rocket flight. A great need still exists for simultaneous measurements.

Environmental sampling methods have been used extensively for investigations in the various scientific disciplines of space research. Although past rocket studies of the ionosphere have favored indirect methods the need for ionospheric measurements at any location and under any condition dictates the use of environmental sampling techniques. Radio propagation methods cannot meet these broad objectives since they measure only one ionization parameter and become severely handicapped (Reference 3), if not completely useless, when irregularities are present in the ionosphere. The major disadvantage of environmental methods is their sensitivity to local disturbances produced in the immediate neighborhood of the space vehicle. With proper precautions local contamination can be minimized, and with competent evaluation of the remaining local effects accurate results can be obtained.

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Two rocket flights were recently conducted for the specific purpose of testing several direct sampling methods which are being developed for synoptic investigations of ionospheric parameters. Although both flights were successful, only the preliminary results from the second and more successful are reported here. This rocket (NASA 4.07), an Aerobee-Hi, was flown in the auroral zone to an altitude of 220 km at midday on September 14, 1959.

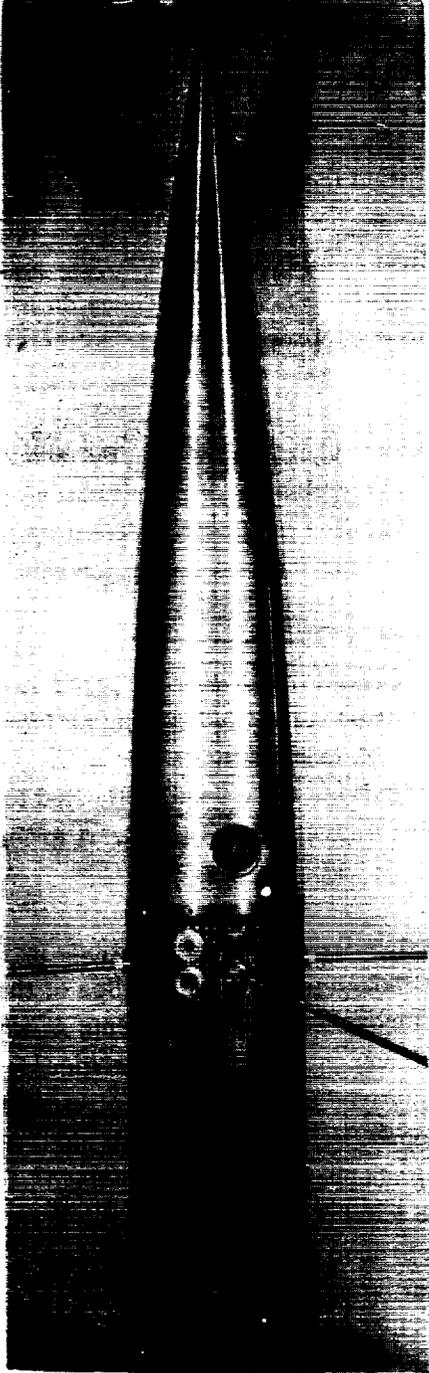


Figure 1 - Nose cone of NASA Aerobee-Hi rocket 4.07, launched 12 September 1959

In order to check electron density measurements the rockets were launched into a uniform ionosphere, under which condition a fairly accurate profile can be calculated from ground P' - f soundings. Seddon's cw propagation experiment was included in the rocket instrumentation since it provides reliable results for soundings into a quiet ionosphere. The environmental sampling sensors which were investigated include a radio-frequency impedance probe, an ion trap, a Langmuir probe, and an electric field meter. These measure respectively electron concentration, ion density, electron temperature, and vehicle surface charge density. Each of the above sensors can measure more than one parameter, but they are best suited for the individual measurements indicated.

The locations of the instruments on the rocket nose cone are shown in Figures 1 and 2. The rocket-borne cw propagation transmitter was deactivated periodically, and consequently the resulting electron density profile was obtained in dashed form. This was done so that direct measurement data could be obtained in the presence of minimum rf field disturbances. Assurance of quiet ionospheric conditions was obtained by continuous monitoring from ground-based P' - f stations. The ionosphere was especially uniform during the flight which occurred one hour subsequent to a radio blackout, as was evidenced by a complete lack of distortion of the beat notes recorded by the cw propagation receivers. Optical and magnetic aspect were measured throughout the flight. The latter data showed that the rocket was essentially vertically oriented during flight.

## THE RF IMPEDANCE PROBE EXPERIMENT (Kane and Jackson)

The rf probe experiment was devised as a result of several rocket flights made in order to observe the effect of the ionosphere on the performance of low-frequency rocket-borne antennas. It was found that antenna capacitance changed by an amount proportional to the ambient electron density. The effects noted, however, yielded electron densities too small by a factor of 3 (Reference 4). This discrepancy was attributed to the presence of large rf fields on the antenna. The correctness of this conclusion

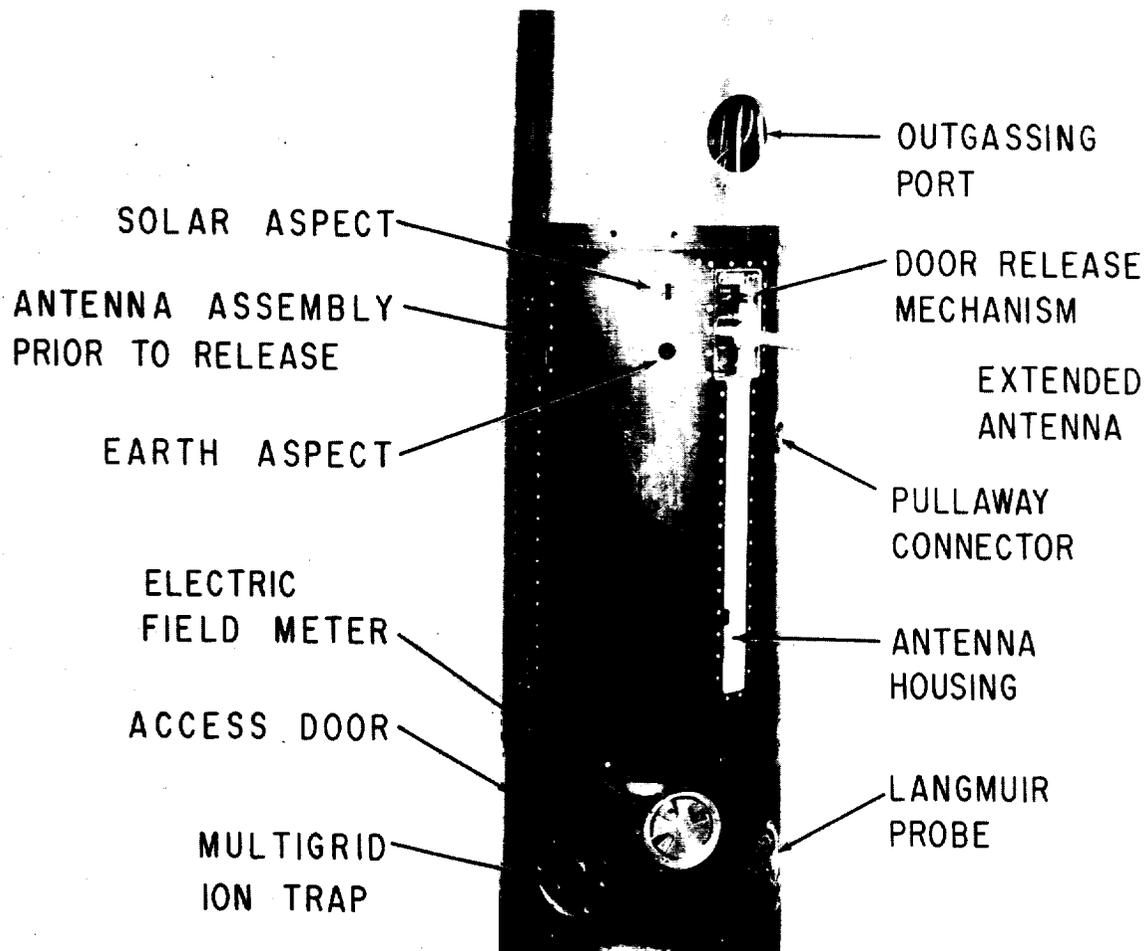


Figure 2 - Sensor locations in NASA Aerobee-Hi rocket 4.07

was established with the NASA 4.07 experiment, in which the use of low rf fields considerably improved the accuracy of the measurements.

The capacitive detuning of a rocket-borne probe consisting of two collinear whips, each approximately 0.6 cm in radius and 6.0 m in length, was measured at 7.75 Mc. If it is assumed that in the ionosphere the probe capacitance  $C$  is related to the free-space capacitance  $C_0$  by the formula  $C = KC_0$ , the local electron density can be computed from the simplified Appleton-Hartree formula for dielectric constant:

$$K = 1 - \frac{81 N_e}{f^2}$$

where  $N_e$  is the electron concentration per  $\text{cm}^3$  and  $f$  is the exploring frequency in kilocycles.

The electron densities obtained by the propagation and probe methods from NASA 4.07 are compared in Figure 3. Both profiles are in agreement concerning the absence of a significant valley above the maximum of the E region. (The descent part of the propagation experiment has not yet been analyzed.) Two general considerations must be taken into account in comparing the two methods: (1) The ability to define the shape

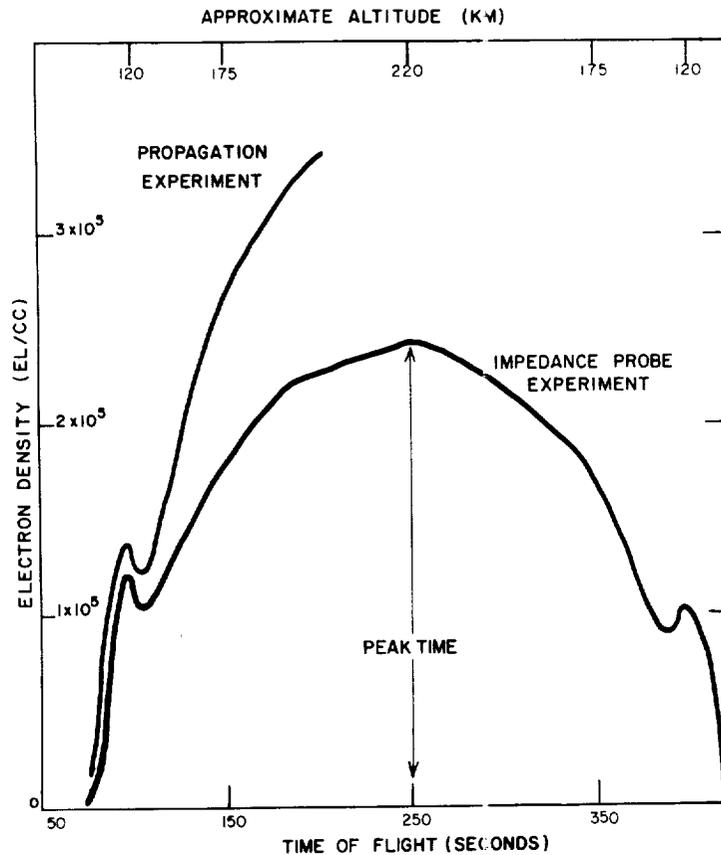


Figure 3 - Electron density vs. time of flight for NASA rocket 4.07

of the electron density profile under all flight conditions, and (2) the absolute accuracy of the derived electron concentrations. With regard to the first consideration, the data from the propagation experiment near the peak of the trajectory are not plotted because of unusable fluctuations due to the high horizontal and low vertical velocity components of the rocket. This reflects one disadvantage of this particular propagation experiment for satellite applications. However, the cw propagation data which are plotted have errors of the order of only a few percent.

It is seen from Figure 3 that the propagation method yields electron densities greater than those from the probe method by a ratio varying from 1.2 at 100 km to about 1.5 at 210 km. This improvement over the previously reported factor-of-3 disagreement between the two methods is due to the fact that the probe measurements were performed at a reduced rf power level. The remaining discrepancy is attributed to the effects on the probe method of vehicle-induced disturbances, the most serious of which is the formation of an ion sheath enveloping the rocket and the probe. The discrepancy can be explained entirely by a probe-enclosing sheath whose thickness varies from 1.5 cm at 100 km to 3.5 cm at 210 km. Calculated values of the thickness of this sheath, assuming charge diffusion under thermodynamic equilibrium to be the only contributing mechanism, are 1.1 cm at 100 km and 1.6 cm at 200 km. The results obtained from other environmental sampling experiments in the NASA rocket show that even larger sheath thicknesses can be expected.

The accuracy achieved with the rf probe experiment is already satisfactory for use in the disturbed ionosphere and for resolving orders of magnitude in the exosphere. If higher accuracy is desired for other ionospheric studies, the absolute error can be reduced considerably by taking the sheath observations from the NASA rocket into account or by making further refinements in the experiment itself.

## **EVALUATION OF THE ROCKET ION SHEATH** (Bourdeau and Serbu)

In addition to measurements of the electron temperature and of the sheath field the Langmuir probe and electric field meter data from NASA 4.07 provide information on the characteristics of the rocket's ion sheath which explain the larger corrections needed for the rf probe experiment. It is of interest to compare the experimental sheath characteristics with the model derived from generally accepted kinetic theory.

In using kinetic theory, previous workers neglected photoemission and the presence of rf fields. The kinetic theory considers a neutral plasma, consisting of positive ions and electrons, into which is inserted a plane conducting body. Owing to the higher velocities of electrons, the body assumes a negative equilibrium potential and consequently is surrounded by a positive ion sheath. The electron current  $I_e$  which flows to the body, is produced only by those electrons energetic enough to overcome the

equilibrium potential. At equilibrium the total current to the body is zero with  $I_e$  balanced by the relatively undisturbed positive ion current  $I_+$ . The potential  $V_q$  is given by

$$V_q = \frac{kT_e}{2e} \ln \frac{T_e M_+}{T_+ M_e}, \quad (1)$$

where  $k$  is Boltzmann's constant,  $T_e$  and  $T_+$  are the temperatures of the electrons and ions, and  $M_e$  and  $M_+$  are their masses. If an ionic constituent of 28 AMU and thermodynamic equilibrium are assumed, this reduces to

$$V_q = 5.4 \frac{kT}{e}, \quad (2)$$

where  $T$  is the kinetic gas temperature.

Expected values of  $V_q$  as a function of altitude are plotted in Figure 4. This curve was computed by averaging two kinetic gas temperature profiles (Reference 5) obtained at the same latitude during two months which bracket the NASA firing. The values are likely to be approximate because Equation 2 assumes plane geometry and because the

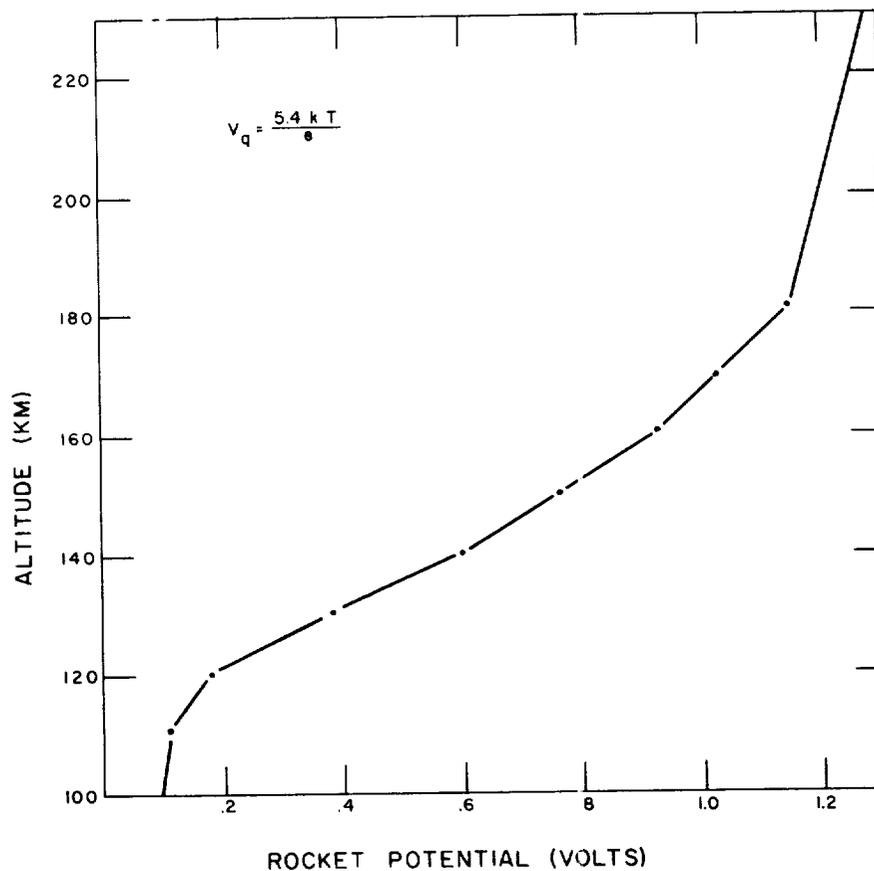


Figure 4 - Expected variation of rocket potential  $V_q$  with altitude

kinetic gas temperatures were obtained indirectly from scale-height measurements on an assumption that the molecular weight of air was 28.9 over the entire altitude range.

The thickness of the ion sheath surrounding the rf probe was computed from the rocket potential of Figure 4, with an analytic relationship for cylindrical geometry (Reference 6). The values obtained (1.1 cm at 100 km and 1.6 cm at 210 km) are not enough to explain completely the difference between the electron densities derived from the cw propagation and the rf probe experiments.

We shall consider now the model of the ion sheath as experimentally observed on the NASA 4.07. First: measurements of current density made by the electric field meter when pointed at the sun show that, for the altitudes considered here, the contribution of photoemission current to the total rocket potential can be neglected justifiably. Second: the Langmuir probe data show rocket potentials which are about twice those plotted in Figure 4. The higher rocket potential is attributed in part to the rectifying action of the telemetry and beacon antennas and in part to ambient electron temperatures higher than the kinetic gas temperatures of Horowitz and LaGow (Reference 5).

Sheath thicknesses computed from the measured potentials and sheath fields are of the order of 1 to 2 cm at the rocket body. These thicknesses should not be confused with those of the rf probe sheath since the geometry is different. Experimental sheath thickness data are presented here because some theoretical studies speculate on sheath dimensions several times greater than this (Reference 7) for altitudes between 100 and 200 km.

Unfortunately the Langmuir probe measurements of rocket potential have not been analyzed completely; consequently, point-by-point correction of the rf probe results based on experimental values of this potential cannot be made at present. However, the higher observed rocket potentials are in the right direction and of about the proper magnitude to explain the required rf probe corrections.

## **THE LANGMUIR PROBE EXPERIMENTS** (Bourdeau and Serbu)

Direct measurements of electron temperatures are needed to resolve the important question of thermodynamic equilibrium. Electron temperatures have been measured indirectly from satellite observations of vehicle potential (Reference 8) and directly by the use of a double-probe version of the Langmuir probe (Reference 9).

The experiment conducted on the NASA rocket is the single-probe version of the Langmuir probe in which the current  $I_p$  to an exposed circular plate is measured as a function of the voltage  $V$  between the plate and the rocket skin. The work of Langmuir offers the theoretical background for the experiment which bears his name. The analysis performed thus far is illustrated in Figure 5. A theoretical A and an experimental

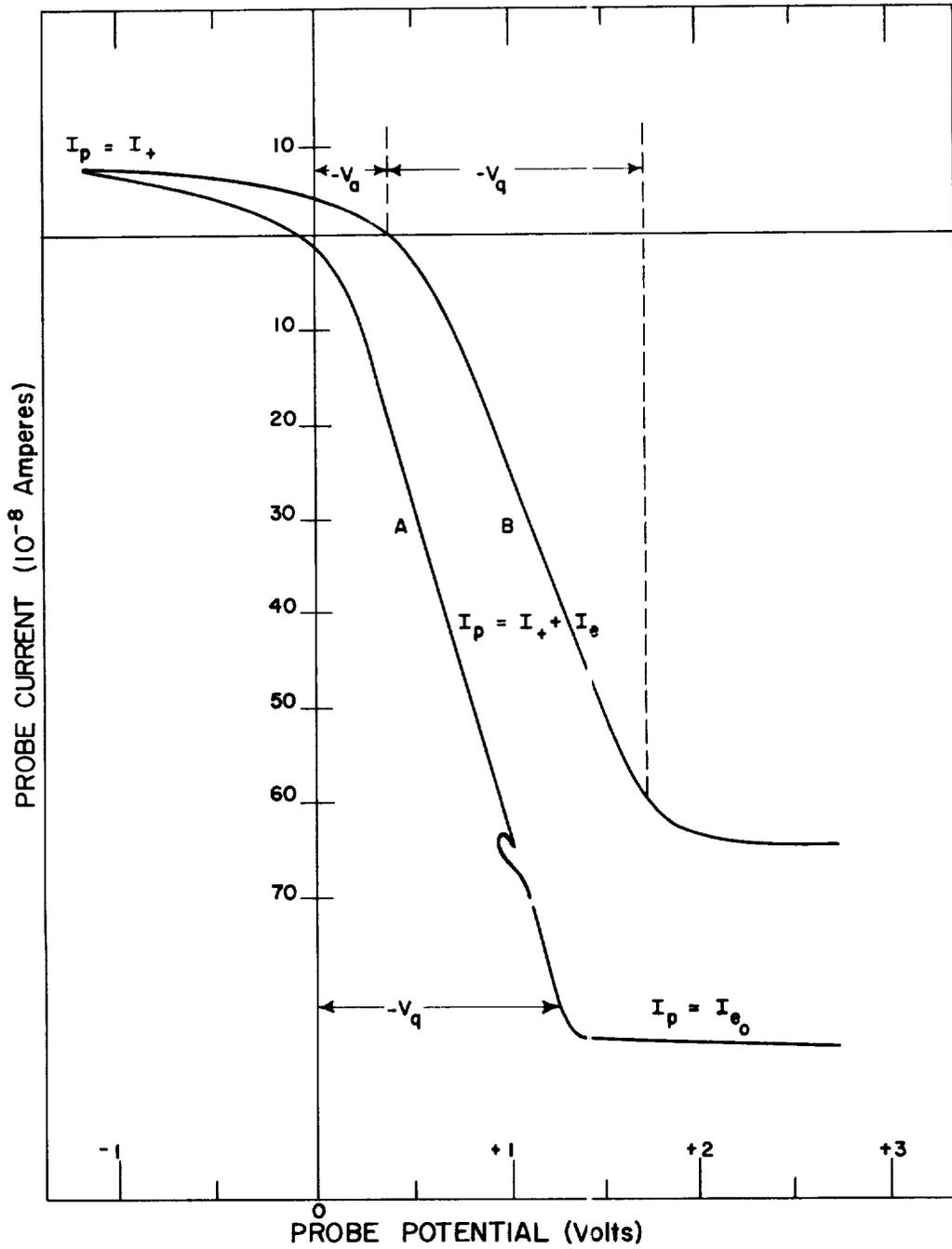


Figure 5 - Theoretical A and experimental B Langmuir probe curves for an altitude of 180 km

B curve are presented, corresponding to an altitude of 180 km. The abscissa is the potential  $V$  of the probe relative to the rocket skin. The theoretical curve is based on thermodynamic equilibrium, Maxwellian distribution of positive ion and electron energies, and Langmuir's simplified theory for plane geometry. Considering first the theoretical curve, for large negative values of  $V$ ,  $I_p$  is a space-charge-limited positive ion current given by

$$I_p = I_+ = \frac{N_+ e \bar{c}_+ A}{4}, \quad (3)$$

where  $\bar{c}_+$  is the average ion velocity and  $A$  the effective collection area. In the region between the large negative and positive values of  $V$ ,  $I_p$  is the sum of the electron and ion currents. The electron current in this region is given by

$$I_e = I_{e_0} \exp \frac{-Ve}{kT_e}, \quad (4)$$

where  $I_{e_0}$  is the undisturbed electron diffusion current. A log plot of Equation 4 yields a straight line whose slope is a measure of the electron temperature. This measurement is independent of the ambient electron density. For large positive values of  $V$  the probe current is the space-charge-limited electron current  $I_{e_0}$  given by Equation 3 with the signs reversed. The rocket potential due to diffusion alone,  $V_q$ , is given by the negative value of  $V$  read at the sharp break in the  $I-V$  curve, this being the point where the probe changes polarity with respect to the plasma.

The experimental curve in Figure 5 is typical of the few volt-ampere curves examined thus far. Even the interpretation of the individual curves is preliminary. The measured rocket potential of -1.7 volts is higher than the theoretical value of -1.1 volts at 180 km from Figure 4. It is composed of two additive components  $V_a$  and  $V_q$ .

The bias or shift of the overall curve,  $V_a$ , is attributed to the rectifying action of the beacon and telemetry antennas. This shift should not affect the electron temperature measurement. The largest error in computing the temperature from the appropriate slope occurs in the correction which must be made for the positive ion current. For the curve shown, if a constant correction corresponding to the  $I_+$  at the largest negative values of  $V$  is made, the result is an upper limit of approximately 7000°K for  $T_e$  at 180 km. With this assumption the upper limit for the observed electron temperatures over the altitude range averages twice the kinetic gas temperatures observed by Horowitz and LaGow (Reference 5). A more refined ion current correction based on the ion trap data could lead to lower electron temperatures. It is expected, however, that the lower limit will still be in excess of the gas temperature reported by Horowitz and LaGow.

Even though the present interpretation of the data is preliminary, it appears probable that ionospheric electron temperatures can be measured with plasma probes. This will

One of the disadvantages of plane geometry is the susceptibility to photoemission from the collector. It was demonstrated in the NASA rocket that this current can be taken into account by obtaining several volt-ampere curves per roll and measuring solar aspect.

## CONCLUSIONS

Four significant results have been obtained by a preliminary analysis of data from the September 1959 rocket firing designed to test the accuracy of the following ionospheric environmental-sampling experiments: a radio-frequency impedance probe for the measurement of electron concentration, a Langmuir probe for electron temperature, and an ion trap for positive ion concentration. The techniques are now considered important for studies of ionized regions, including the interplanetary plasma.

The first important result is that all the experiments flown, including a supporting electric field meter experiment, are internally consistent in describing an ion sheath about twice as thick as that expected on the basis of simplified kinetic theory. Part of this factor of 2 is possibly due to rf field disturbances. An accurate knowledge of the sheath characteristics is important since this information can be used to improve the accuracy of all environmental sampling techniques.

The second important result is that the accuracy of the rf probe electron density measurement was improved as compared to previous rocket flights, by obtaining data at reduced rf power levels. Electron densities measured in the recent NASA rocket flights by a cw propagation experiment were 1.2 to 1.5 times those obtained by the rf probe at altitudes of 110 km and 210 km, respectively. This remaining discrepancy is explained by an ion sheath having dimensions consistent with those measured by the companion experiments. More accurate results can be obtained by taking this ion sheath into account.

The third important result is that the single-probe version of the Langmuir probe was found to be well adapted to the measurement of electron temperatures in the ionosphere. This conclusion is based on the fact that reasonable electron temperatures were obtained from the NASA rocket measurements through the use of theories developed by Langmuir and Boyd in their laboratory studies of gaseous discharges. A preliminary data analysis reveals electron temperatures in excess of the kinetic gas temperatures measured by other observers at the same latitude, but possibly under different atmospheric conditions.

The fourth result is the measurement of positive ion concentrations approximately equal to the electron densities observed experimentally from the cw propagation experiment. The ion concentration values were obtained by using Boyd's observation that the ion current is governed by the ambient electron temperature. This analysis would not

apply to ion traps on satellites, since in that case the ion collection volume is determined by the known satellite velocity.

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## REFERENCES

1. Seddon, J. C., "Propagation Measurements in the Ionosphere with the Aid of Rockets, J. Geophys. Res., 58(3):323-335, September 1953
2. Jackson, J. E., "A New Method for Obtaining Electron Density Profiles from P' - f Records," J. Geophys. Res., 61(1):107-127, March 1956
3. Jackson, J. E., and Seddon, J. C., "Rocket Measurements Through an Aurora," IGY Bulletin No. 28, October 1959
4. Jackson, J. E., and Kane, J. A., "Measurement of Ionosphere Electron Densities Using an RF Probe Technique," J. Geophys. Res., 64(8):1074-1075, August 1959
5. Horowitz, R., and LaGow, H. E., "Summer-Day Auroral Zone Measurements from 100-210 Kilometers," J. Geophys. Res., 63(4):757-773, December 1958
6. Jastrow, R., and Pearse, C. A., "Atmospheric Drag on the Satellite," J. Geophys. Res., 62(3):413-423, September 1957
7. Imyanitov, I. M., "Measurement of Electrostatic Fields in the Upper Layers of the Earth's Atmosphere," Uspekhi Fizicheshikh Nauk, 63(1b):267-282, September 1957
8. Krassovsky, V. I., "Exploration of the Upper Atmosphere with the Help of the Third Soviet Sputnik," Proc. IRE 47(2):289-296, February 1959
9. Boggess, R. L., Brace, L. H., and Spencer, N. W., "Langmuir Probe Measurements in the Ionosphere," J. Geophys. Res., 64(10):1627-1630, October 1959
10. Loeb, L. B., "Basic Processes of Gaseous Electronics," 346-353, Berkeley, University of California Press, 1955

11. Schulz, G. J., and Brown, S. C., "Microwave Study of Positive Ion Collection by Probes," *Phys. Rev.*, 98(6):1642-1649, June 1955
12. Whipple, E. C., "The Ion Trap Results in 'Exploration of the Upper Atmosphere with the Help of the Third Soviet Sputnik'," *Proc. IRE* 47:2023-2024, November 1959